Heliyon 10 (2024) e29238

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Assessing the cooling/lubricating agencies for sustainable alternatives during machining of Nimonic 80: Economic and environmental impacts

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ARTICLE INFO

Keywords:
Machining
Nimonic 80
Vegetable oil
Hybrid nanofluid-MQL
LCO_2
Sustainability analysis
Machining costs
Carbon emissions

ABSTRACT

Developing sustainable manufacturing methods that balance environmental and economic aspects is challenging. A comprehensive analysis of the economics of machining and carbon emissions is essential to encourage adopting sustainable practices. This work presents the machinability and comparative sustainability analysis of Nimonic 80 superalloy when it is machined utilizing a novel, environmentally friendly vegetable oil-based hybrid nanofluid-minimum quantity lubrication (MQL) and liquid carbon dioxide (LCO_2) technique. The main objective is to comprehend the efficacy of the proposed approach on tool life, surface roughness, power consumption, total machining costs, and carbon emissions. Compared to other machining conditions, the use of hybrid nanofluid-MQL under 100 m/min cutting speed prevented rapid flank wear and considerably increased tool life by about 17–59 %. The change in cutting speed from 100 to 150 m/min has resulted in reduced tool life about 13–42 % under the selected environments. In addition, when compared to dry, flood, and MQL machining, the use of hybrid nanofluid-MQL and LCO_2 reduced surface roughness by around 16–45 % at 150 m/min. Sustainability analysis revealed that machining at 150 m/min resulted in decreased costs ranging from 6.1 % to 36.4 % for selected cutting environments. Applying hybrid nanofluid-MQL lowered carbon emissions by 16.83 %, whereas LCO_2 reduced carbon emissions by 14.6 % at 100 m/min. At 150 m/min, hybrid nanofluid-MQL and LCO_2 lowered carbon emission by 22.3 % and 21.5 % at 150 m/min compared to dry machining. Compared to alternative cutting environments, hybrid nanofluid-MQL and LCO_2 applications have longer tool lives, lower machining costs, and carbon emissions. As a result, they are economical and environmentally friendly.

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https://doi.org/10.1016/j.heliyon.2024.e29238
Received 15 November 2023; Received in revised form 28 March 2024; Accepted 3 April 2024
Available online 8 April 2024

Nomenclature and abbreviations

MQL	Minimum Quantity Lubrication
nMQL	Nanofluid minimum quantity lubrication
AISI	American Iron and Steel Institute
LCO_2	Liquid Carbon-dioxide
LN_2	Liquid nitrogen
MoS_2	Molybdenum disulfide
hBN	Hexagonal boron nitride
MWCNTs	Multi walled carbon nanotubes
Al_2O_3	Aluminium oxide
PVD	Physical vapour deposition
TiAlN	Titanium aluminium nitride
$C_{total\ cutting}$	Cost for machining
C_{lmt}	Labour and machine tool utilization cost
C_{cf}	Cutting fluid utilization cost
C_{ct}	Cutting tool cost
C_{power}	Power consumption cost
C_{waste}	Waste management and processing cost
CE_{total}	Total carbon emission from CNC machining
CE_{power}	Carbon emissions from power consumption
CE_{ct}	Carbon emissions from cutting tool
CE_{cf}	Carbon emissions from cutting fluid
$CE_{material}$	Carbon emissions from workpiece material
CE_{cr}	Carbon emissions from chips recycling

1. Introduction

Superalloys based on nickel exhibit superior characteristics, such as improved fatigue life, the ability to maintain mechanical and chemical properties at high operating temperatures, and resistance to creep, wear, corrosion, and thermal shock. Because of these outstanding qualities, they are used in various critical applications, including aerospace, heavy engineering, and nuclear reactors [1]. Due to the poor thermal conductivity of these alloys, a substantial quantity of heat is transmitted to the cutting tool during machining. Because of this, turning these alloys results in much heat, impacting the surface quality produced on the workpiece and tool life [2]. Dry machining of difficult-to-cut material was carried out to optimize the turning parameters to reduce surface roughness. A second-order polynomial regression model was developed to establish the effect of cutting speed, feed rate, and depth of cut on cutting force and vibration under dry turning. It was reported that the machining vibration was significantly affected by cutting speed, followed by feed rate and depth of cut [3]. Therefore, the researchers have employed mineral-based cutting oils for cooling and lubricating purposes in wet/flood turning to improve the machining performance [4,5]. However, due to their synthetic origin, these mineral fluids have negative consequences such as non-renewability, high toxicity, effects on the health of the workforce, and the cost of manufacturing [6,7]. In order to address these problems and replace flood lubrication, most researchers nowadays have turned to effective and environmentally beneficial methods.

Minimum quantity lubrication (MQL) is one of the alternatives explored and reported in previous studies [8]. In the MQL technique, small quantities of fluid (5–200 ml/h) and compressed air are atomized at the cutting zone for cooling and lubricating action [9]. The cooling effect is produced by the evaporation of lubricating oil and the predominant convective heat transfer caused by compressed air [10]. Several studies reported that machining with MQL and biodegradable oils can extend tool life and improve turning performance [11]. Under MQL, several vegetable oils, solid lubricants, and nanoparticles have been studied to further increase the sustainability in turning [12,13]. A comprehensive review of the applicability of electrostatic atomization was presented to improve the MQL performance. With the action of an electric field, the electrostatic spray can produce oil droplets with smaller and uniform particle sizes. Additionally, the effect of bio-lubricants with atomized droplets in form of increased penetration depth was discussed. The synergic effect of nano-bio lubricants on machining performance in the form of reduced friction and temperature at the cutting zone was also discussed [14]. Various test methods and technologies for materials were discussed in the direction of solid lubrication application. The work presented important insights into the friction properties and wear mechanisms of molybdenum disulfide (MoS_2), carbon, and polymeric materials. It was concluded that the formation of transfer films can improve the effectiveness of solid lubricant [15]. Nevertheless, MQL is ineffective in providing efficient cooling at higher temperatures produced during the machining of high-strength alloys [16]. As a result, it is essential to enhance the cooling capabilities of MQL. In this direction, mono and hybrid nanoparticles in MQL fluid have drawn the attention of researchers to improve MQL performance [17]. The lubrication efficiency of the lubricant mixture can be enhanced by adding nanoparticles. Due to their superior solid-state tribological performance, strong thermal conductivity coefficient, and outstanding lubricating qualities, nanoparticles are a viable choice for lubrication [18]. Nanofluid is the colloidal liquid formed when nanoparticles are added to a base liquid. When creating nanofluid mixtures, nanoparticle sizes are typically desired in the 1–100 nm range but are not yet standardized [19]. Including nanoparticles can form an effective tribo-film between surfaces, thus minimizing friction, wear, and heat generation [20]. To examine the friction and wear performance of dry, sunflower oil, Cuo, and ZnO nanofluid with/without surfactant, Yildirim et al. [21] conducted experimental studies while machining waspaloy. The ZnO and PolyVinyl Pyrrolidone mixture improved tool wear, surface roughness, and cutting temperature by 53.9 %, 36.52 %, and 44 %, respectively, compared to dry machining. A reduction in the coefficient of friction (CoF) in the first 500 s of the test. PVD surfactant-doped CuO and ZnO nanofluids produced lower CoF with a stable lubricant film. The machinability of nickel-based superalloys using dry, biodegradable coolants and various nanofluids was studied by Chetan et al. [22]. The tribo-film and ball bearing effects, which would improve the machinability of superalloys, were discovered thanks to the investigation. Aluminium oxide (Al_2O_3) NFs at 125 ml/h flow rate with low surface tension resulted in lower cutting force due to tribo-film formation. Numerous experimental investigations using nano-MQL as a cooling technique discovered that nanofluid reduces cutting temperature and friction at the tool-chip interface more effectively. Additionally, it was noticed that cutting fluids had better wettability and lubricity [23]. Amrita et al. [24] applied nano-graphite MQL during the machining of AISI 4140 alloy and found the efficiency of MQL with nanofluid in terms of lowering cutting temperature and tool wear. It was attributed to the improved lubrication of nano-graphite and cooling through compressed air supplied in MQL. Yildrim et al. [25] investigated the impact of several mono and hybrid nanofluids made from MoS_2, Al_2O_3, and MWCNT during the turning of SAE 420 alloy. The work reported improvement in surface topography due to thin oil film, which has reduced friction at the tool-chip interface. Tool wear under mono and hybrid MQL environments was considerably reduced compared to dry and base fluid MQL. Makhesana et al. [26] investigated the role of MQL applied with vegetable oil and $nMoS_2$ MQL while machining Inconel 690. The thermo-physical properties of the developed nanofluid with different concentrations (0.5 %, 1 %, and 1.5 %) were analyzed. In comparison to dry, flood, and MQL turning, findings showed that nanofluid minimum quantity lubrication (nMQL) reduced surface roughness by 54 %, 29 %, and 13 % and lowered consumption of energy by 56 %, 39 %, and 12 %. Bilgin et al. [27] utilized different cutting environments to assess their effect on machinability and microstructural properties during machining Nickel-based superalloy Inc-718. The inclusion of Al_2O_3, SiC and MWCNT nanoparticles resulted in higher viscosity compared to base fluid. The application of nanofluid, particularly Al_2O_3 nanofluid resulted in reduced surface roughness from 37.5 to 62.8 %. It was reported that the preheating of Inc-718 workpiece and improved lubrication of Al_2O_3 nanofluid noticeably reduced cutting forces and vibrations. In a recent work, the machinability characteristics of Inconel 713C was investigated by applying graphene-based solid lubricants and a novel honeycomb and broken-parallel texture cutting inserts [28]. The honeycomb texture and graphene combinely reduced cutting temperature, force, surface roughness, and tool wear by 22.4 %, 39.4 %, 22.4 %, and 2.3 %, respectively. This is mainly attributed to the reduced friction co-efficient with tool texture and graphene which has also reduced the chip-curl diameter compared to dry conditions.

Cryogenic machining is one of the environmentally-conscious ways to process high-strength and heat-resistant alloys. Coolants like liquid nitrogen (LN_2) and liquid carbon dioxide (LCO_2) are used during environmentally beneficial cryogenic machining. In addition to being more efficient in terms of cost, cryogenic machining is more efficient than conventional cooling techniques. LN_2 and LCO_2 assist in carrying away the chips produced while machining, lower the cutting temperatures, and can be viewed as a sustainable manufacturing method [29,30]. Rotella et al. [31] evaluated the outcomes achieved under dry and MQL circumstances while analyzing surface integrity resulting from cryogenic cooling while machining Ti–6Al–4V alloy. Cryogenic machining has been reported to improve surface quality and overall performance. Sun et al. [32] studied the machining performance of Ti-5553 in a cryogenic environment and compared it with MQL and flood cooling techniques. Cryogenic machining reduced tool wear, cutting force, and surface roughness by approximately 30 %. The less friction and adhesion on the tool cutting edge produced lower cutting force by avoiding severe plastic deformation at a low feed rate. A hybrid cryo-MQL approach was utilized by Shokrani et al. [33] to compare with flood cooling while machining titanium alloy. They found that tool life increased thirty times and surface finish improved by around 50 % over flood machining. A noticeable reduction in the form of crater and diffusion wear was reported even at high cutting

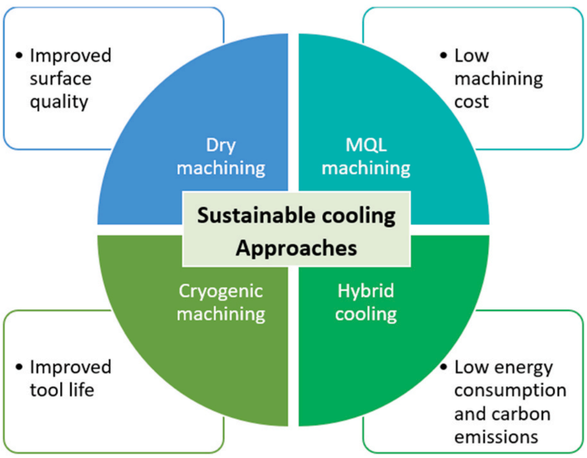

Fig. 1. Various sustainable cooling approaches.

speeds due to the effective cryogenic cooling. Sartori et al. [34] examined the influence of different cooling environments, such as dry, wet, MQL, LN_2, CO_2, CO_2+MQL, and LN_2+MQL, during turning Ti–6Al–4V alloy. Findings have shown that high flow rates and hybrid cooling conditions extended tool life and reduced surface roughness. The low temperature generated with LN_2 and LCO_2 prevents diffusion, lowering the adhesion by controlling heat generation. Jerold and Pradeep Kumar [35] investigated the effects of flood, LN_2, and CO_2-cryogenic cooling on surface roughness, cutting forces, temperature, and chip forms during machining AISI-1045 steel. They found that emulsion and CO_2- cryogenic cooling has 9–34 % and 3–17 % lower temperatures, respectively, than LN_2. Comparatively to the emulsion and LN_2, CO_2 reduced the cutting forces by 17–38 % and 2–12 %, respectively. Pereira et al. [36] performed experimental investigations under cryogenic and MQL machining. Cryogenic cooling was found to reduce tool wear by 50 %. A non-uniform surface topography under dry machining was reported, whereas cryoMQL resulted in better surface topography with a stable process. The life cycle analysis results suggested MQL as one of the suitable alternatives for technical improvement and minimum ecological effects.

Sustainable machining is the machining operation that has the minimum negative impacts on the environment, human health, energy conservation, carbon emissions, and cost-effectiveness (Fig. 1). It has been observed that high-strength and heat-resistant alloys cannot be machined effectively using traditional machining methods. These methods could be unsustainable and less productive. Many attempts are being made to incorporate the sustainability factor in machining. Due to the poor thermal conductivity of these alloys, a substantial quantity of heat is transmitted to the cutting tool during machining. Because of this, turning these alloys results in much heat, impacting the surface quality produced on the workpiece and tool life [2]. Therefore, the researchers have employed mineral-based cutting oils for cooling and lubricating purposes in wet/flood turning in the industrial sector [37,38]. These initiatives are crucial because we must preserve the available resources and save our environment. Since the manufacturing sector is one of the largest, it is imperative to integrate sustainability into this field [39]. They conducted research on turning AISI P20 under dry and flood cooling and analyzed the amount of electrical energy and metalworking fluid utilized, material removal rate, and surface finish produced. Wet machining had less influence on the environment and energy consumption when turning AISI P20 than dry machining. Pereira et al. [40] analyzed the sustainability of different vegetable oil-based lubricants for machining Inconel 718. The tribological and rheological properties of the fluid mixture were evaluated, and a life cycle analysis was presented. The integration of low viscosity with high friction co-efficient resulted in longer tool life. It was concluded that sunflower oil improved tool life by 15 % compared to canola oil. Khanna et al. [41] investigated the sustainability and environmental effects durin machining 15-5 PH stainless steel by combining different cutting fluids, feed rate, and cutting speed. As an outcome, it has been discovered that dry machining has the highest energy consumption whereas hybrid nanoparticles immersed EMQL (HNPEMQL) consumed lower energy. A life cycle analysis for selected machining environments was presented to understand the environmental burden created from their use. Javid et al. [42] performed a one-step sustainability assessment for turning HSLA steel in varied cutting conditions. They recommended employing $nSiO_2$-assisted MQL than base fluid MQL since it uses less energy and has superior surface integrity, lower tool wear, and associated expenses. The effectiveness of cryogenic ultrasonic-assisted turning-minimum quantity lubrication (UAT-MQL) and cryogenic UAT was studied by Chetan et al. [43]. It was concluded that, compared to cryogenic assisted turning, the energy used by the machine tool could be reduced by around 1.8–3.6 % by employing hybrid approaches. Hybrid turning techniques can reduce surface roughness values by approximately 32%–42 % compared to cryogenic-assisted turning.

The studies that have been published examined the machining performance of nickel-based alloys and have found it to be a difficult-to-cut material. Machining responses have been extensively investigated while turning these alloys using various cooling/lubricating approaches. However, it is a present-day need and essential to quantify the sustainability of these approaches. It has been observed from the literature that the use of MQL, cutting fluids based on vegetable oil, cryogenic cooling, and other hybrid approaches have demonstrated improvements in machinability. To the best of the authors' knowledge, the comparative assessment of hybrid nanofluid-MQL and LCO_2 during machining Nimonic 80 is not reported in the available literature. Furthermore, the accessible literature does not provide a systematic sustainability evaluation of such hybrid solutions. Due to the widespread use of this material today, the overall machining costs and carbon emission reductions during processing are crucial for sustainability. In this context, the following research gaps are filled by the current study.

- Machinability investigations of Nimonic 80 using environmentally conscious cooling/lubrication techniques.
- Tool life, surface roughness, and power consumption are evaluated to comprehend machinability.
- Detailed sustainability assessment by considering machining costs and carbon emissions during machining Nimonic 80 using dry, flood, MQL (vegetable oil), hybrid nanofluid-MQL (vegetable oil), and LCO_2 strategies.

Additionally, limited information about the machinability and long-term sustainability of Nimonic 80 is available under hybrid vegetable oil-based nanofluid-MQL and LCO_2. Therefore, this study attempts to evaluate the machining performance of Nimonic 80 and to assess and improve its sustainability. This study examined machining response by considering tool life, surface roughness, power consumption, and sustainability evaluation considering overall machining cost and carbon emissions. The machinability is evaluated at 100 m/min and 150 m/min cutting speeds. A detailed analysis of total machining costs and carbon emissions is presented to provide a better perspective of sustainability assessment. The second section presents information about materials and methods, experimental set-up and methodology, machining environments, and measurement of responses. The third section comprises results and discussions and is divided into two parts: The first part presents machinability evaluation, and the second part includes sustainability assessment. The last section presents the conclusions of the study.

2. Materials and methods

2.1. Workpiece and cutting tools

The current investigations use cylindrical Nimonic 80 bars 500 mm long and 50 mm in diameter as the workpiece material. Alloy 80 (Nimonic® alloy 80) is a wrought, age-hardenable nickel-chromium alloy, and it is being used in many critical industrial applications, including automobiles, aerospace, etc. Table 1 presents the chemical composition of the work material. PVD-TiAlN-coated carbide inserts are utilized for experimental investigations with ISO designation CNMG120408 and a tool holder PCLNL2020K12.

2.2. Experimental set-up and methodology

Experimental investigations are performed on a CNC turning centre with a Siemens controller considering dry, flood, MQL with vegetable oil, hybrid nanofluid-MQL, and LCO_2 environments. The spindle speed of the lathe machine can be varied between 150 and 6000 rpm and has a power rating of 10 kW. The experiments are conducted using cutting speed (v_c) = 100 m/min and 150 m/min, feed rate (f) = 0.10 mm/rev, and depth of cut (a_p) = 0.5 mm for all the experiments. A smaller value of depth of cut is selected to avoid any vibration effects. It has been reported in the available literature that minimum surface roughness can be achieved with a lower depth of cut during machining. As the depth of cut increases, the shear angle increases rapidly, resulting in higher surface roughness due to vibrations [44]. The cutting parameter values are selected based on the preliminary experiments conducted with three different levels of parameters. The cutting length is kept at 100 mm, and each experiment is carried out with a new cutting edge to comprehend the machining performance in a better way. The experimental arrangement, including the methodology adopted, is presented in Fig. 2.

2.3. Preparation of hybrid nanofluid

One and two-step approaches are typically preferred in developing nanofluids [20]. Due to its effectiveness and efficiency, this investigation used the two-step method (Fig. 3). Molybdenum disulfide (MoS_2) with an average particle size of 80 nm was added by 1 vol% in jojoba oil to obtain the nanofluid mixture. In order to prepare a hybrid vegetable oil-based nanofluid, commercially available jojoba oil is mixed with 0.50 vol% MoS_2 (average particle size 80 nm) and 0.50 vol% hexagonal boron nitride (hBN) (average particle size 80 nm) nanoparticles. The nanofluids were prepared by adding nanoparticles by 1 vol%. The volume fraction of nanoparticles in a base fluid was selected based on the review of available literature [12] and previous studies [26,45]. A similar study [43] discussed the effect of 0.5–1.5 % silica added in palm oil and reported higher wettability with 1 % silica. A significant reduction in tool wear was reported with 1–1.25 vol% graphene/alumina nanoparticles added to hybrid nanofluids [46]. Agglomeration is one of the most significant challenges faced when preparing nanofluids. Applications requiring nanofluids have unique requirements, including steady suspension, low particle aggregation, and high chemical and physical stability. To improve the stability of the generated suspensions, a variety of techniques are used, including pH alteration, ultrasonic vibration, and surfactants and dispersants. The chosen surfactant in the current study is sodium dodecyl sulphate (SDS), which is added with 0.25 wt%, and a mechanical stirrer (Daihan HS-100D) was utilized to mix the nanofluid for 10 min. The base fluid was gradually added with nanoparticles during mixing for 30 min. Surfactant and nanoparticles are mixed at 750 rpm for 30 min using an ultrasonic homogenizer (Bandelin Sonopuls HD-3200) with a frequency of 30 kHz. In the last step, a magnetic stirrer at 1500 rpm is used to stir the mixture for 60 min. When MQL was used, a tiny mist was produced, and specific steps were taken to mitigate concerns about employing nano-additives. Additionally, standard nano-additives safety data sheets were referred to maintain a consistent level of health and safety during the experimental phase and avoid any negative impacts on the operator. It is crucial to characterize the nanofluids to determine the stability of the nanofluid suspension. The nanofluids used for cutting have been analyzed using a zeta potential for the stability study. The zeta potential absolute values are calculated using the Zetasizer device for developed nanofluids. The zeta potential values in the range of 40–45 demonstrated the high stability of the prepared nanofluid.

2.4. Machining environments

Different machining environments, including dry, flood, MQL with vegetable oil, hybrid nanofluid-MQL, and LCO_2, were used to analyze the impact of various cooling/lubrication strategies in cutting. The dry machining is performed first without any coolant under the selected cutting parameters (as presented in Table 2). During tests, flood cooling is performed using a commercially available water-soluble coolant diluted at a 1:20 ratio in water until completely dissolved to form a milky white emulsion. The flow rate is kept constant at 25 l/h, and the nozzle size was 5 mm. The HMT CNC turning center with the MQL system mounted is utilized for MQL experiments. The MQL technique is utilized to minimize lubricant usage during machining. A Kenco-made MQL system is used to supply vegetable oil-based lubricant to the cutting zone. To provide sufficient lubricant supply to the cutting zone, the flow rate of MQL

Table 1
Chemical composition of Nimonic 80.

Element	Ni	Al	B	C	Cr	Co	Cu	Fe	Mn	P	Si	S
Weight (%)	Balance	1.7	0.008	0.1	20	0.2	0.2	3.0	1.0	0.040	1.0	0.015

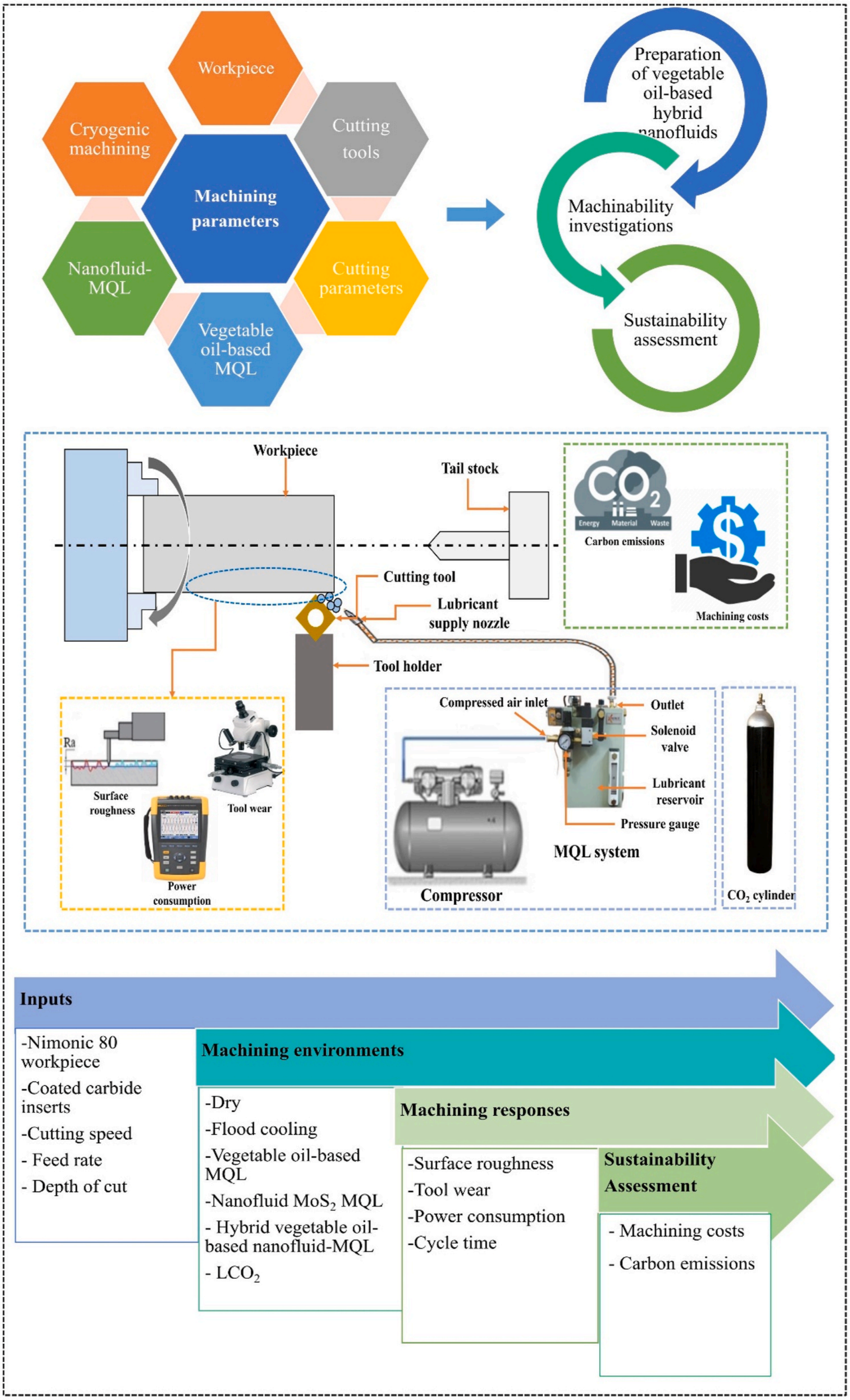

Fig. 2. Methodology of the work, Up) Machine and process setup, Down) input and outputs in experiments.

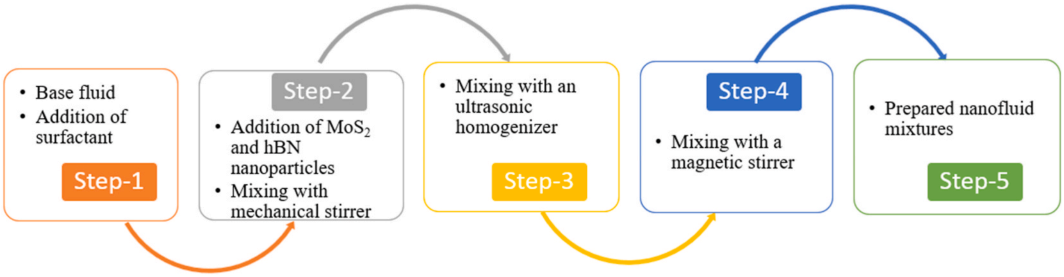

Fig. 3. Procedure of nanofluid preparation.

Table 2
Details of machining parameters and cooling environment conditions.

Category	Specification	
Machine tool	HMT® Starturn center lathe	
Workpiece Material and dimension	Nimonic 80 Ø 50 × 500 mm	
Cutting tool insert	PVD-TiAlN-coated carbide inserts CNMG120408	
Cutting speed, ν_c (m/min)	100, 150	
Feed rate, f (mm/rev)	0.10	
Depth of cut, a_p (mm)	0.5	
Machining conditions	Symbol	Cutting condition
	C1	Dry
	C2	Flood cooling
	C3	Vegetable oil-based MQL
	C4	Vegetable oil-based $nMoS_2$ MQL
	C5	Hybrid vegetable oil-based nanofluid-MQL
	C6	LCO_2

supply is kept constant at 100 ml/h, air pressure 3 bar, nozzle distance and angle 30 mm and 45°, respectively. Cryogenic cooling has been used to lower the cutting temperature while processing hard-to-cut materials because these metals exhibit poor heat dispersion and limited thermal conductivity. Cryogenic machining reduces cutting temperature by removing heat from the cutting area without utilizing cutting fluid [47]. LCO_2 was utilized as a cryogenic coolant in the current investigation to compare its results to dry, flood, nMQL, and hybrid nMQL based on machinability indices. The cooling and lubricating behaviour of LCO_2 results in a decreased friction coefficient at the tool-chip interface and enhances the heat conductivity of carbide-cutting tools [48]. LCO_2 is drawn from a cylinder kept at a pressure of 57 bar and supplied at 6 bar to the machining interfaces. LCO_2 is supplied at a flow rate of 25 l/h. A nozzle with a diameter of 3 mm and a distance of 30 mm is utilized to supply LCO_2 to the cutting zone.

2.5. Measurement of responses

The machining outcomes, namely surface roughness, tool wear, and power consumption, are measured for a comparative study. These responses have significant effects while analyzing machining and sustainability indicators. The tool wear resulting in selected machining environments is essential in understanding the tool life achieved. Tool wear produced during machining is analyzed by Mitutoyo Toolmaker Microscope considering the criteria of ISO 3685. Experiments are stopped when maximum flank wear reaches 0.3 mm, and the life of the cutting tool is considered over. Surface finish produced on machined components plays a significant role in performance. Surface roughness (Ra) produced during various machining conditions is measured by utilizing the Mitutoyo SurfTest-SJ210 surface roughness tester (sample length 0.8 mm, evaluation length 4 mm, and travel length 4.8 mm). The Ra value is measured in the direction of the feed by considering three locations along the length of the machined workpiece, and an average value is taken into account to avoid measurement errors. When evaluating the sustainability of the machining operations, power consumption is a critical factor [49]. A Fluke power analyzer is used to calculate the amount of power used during each machining experiment.

3. Results and discussion

The outcomes of the experimental study are provided in the following section. The machinability evaluation is presented in the first part of this section, while the sustainability assessment is presented in the second. The machinability evaluation examines tool life, surface roughness, and power consumption. The sustainability assessment is carried out by considering economic and environmental aspects, as measured by overall machining costs and carbon emissions of the process.

3.1. Machinability evaluation

3.1.1. Tool life

The cutting performance of tool inserts has a direct impact on machining efficiency. Under different machining conditions, the tool life of cutting inserts used in turning is examined. Fig. 4 provides a visual representation of the tool life achieved under the considered cutting conditions (C1 to C6) at cutting speeds of 100 and 150 m/min. It can be seen that higher cutting speeds lead to a decrease in tool life for all machining conditions, including different cooling systems. The decrease in tool life is attributed to the elevated temperatures generated during high-speed cutting. When machining nickel alloy, a substantial amount of heat is produced at the tool-work interface, significantly impacting tool wear. Dry machining exhibits the highest flank wear as a result of the frictional heat, thus resulting in 6 min of tool life under 100 m/min cutting speed. With pure and hybrid nanofluid-MQL application, less average flank wear is seen than flood and dry machining. A much closer analysis of achieved tool life revealed that the highest tool life is achieved under C5 conditions, followed by C6, C3, C4, C2, and C1 conditions at both cutting speeds. Furthermore, the change in cutting speed from 100 to 150 m/min has shown a reduction in tool life across different conditions by 42 % (C1), 13 % (C2), 14 % (C3), 10 % (C4), 21 % (C5), and 13 % (C5). The results demonstrate significant improvements in tool life under the C5 condition at 100 m/min compared to other conditions, as follows: 59 % (C1), 45 % (C2), 24 % (C3), 31 % (C4), and 17 % (C6). Similar outcomes with turning Inconel 625 super alloy were reported [50]. Additionally, compared to low cutting speed, tool wear increased at higher cutting speed, leading to rapid wear of the cutting edge [51]. The primary factor contributing to this effect is the low thermal conductivity of Nimonic 80. When comparing the results to dry turning, it was found that under C2, C3, and C4 conditions, there wa significant improvement in tool life at both cutting speeds. The continual presence of oil in the C2 condition (flood cooling) reduces the amount of tool wear compared to C1. Applying LCO_2 effectively reduced the temperature in the cutting region. It prolonged tool life by maintaining the hardness of the tool in contrast to dry, flood, and MQL machining.

The outcomes mentioned above under the C5 condition result from effective heat conduction and chip removal from the cutting zone accelerated by high-pressure MQL fluids. Additionally, the improved lubricity of vegetable oil and hybrid nanoparticles controlled the frictional forces in the tool-workpiece interface. The high viscosity index, oxidation, and thermal stability of jojoba oil and nanoparticles noticeably resulted in low friction and tool wear [52,53]. Furthermore, it is believed that the presence of nanoparticles with weak van der Waals bonds in nanofluid results in a homogeneous mixture and provides enhanced cooling/lubrication. The availability of nanoparticles helps reduce the friction and formation of a tribo-film layer at the machining interface, resulting in lower tool wear [44,54]. Similarly, work reported [47] compared and discussed the performance of LCO_2 with dry and electrostatic MQL and reported the reduction in tool wear under LCO_2 with a smooth wear progression. A smooth wear progression was observed due to a reduction in cutting zone temperature, which has maintained the hardness of the cutting edge.

Fig. 5 presents the tool wear observed under selected cutting environments. The primary types of wear mechanisms observed under all cutting conditions are abrasive wear, chipping, and nose wear. With most tool materials, abrasion as the wear mechanism was also observed while cutting nickel alloys [55]. Dry machining caused significant tool wear at selected cutting speeds since coolant or lubricant was not employed. However, the availability of cooling or lubrication in other cutting conditions considerably lowered tool wear and improved tool life. As the cutting time goes on, the increased built-up edge formation on the cutting-edge leads to wear types in the cutting tool, like abrasion and chipping [56]. Therefore, the built-up edge and higher abrasion are believed to be observed on the cutting tool under dry conditions. The development of high cutting temperatures and cutting pressures during dry cutting served as a foundation for this circumstance.

Under flood cooling and MQL application, cutting-edge abrasion and chipping are noticed. A built-up edge forms due to the high temperature resulting from the limited heat conductivity and chemical reaction between the workpiece and the tool material. When

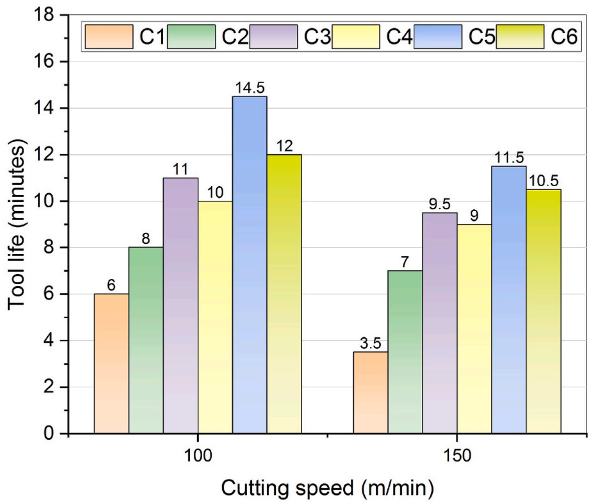

Fig. 4. Tool life produced under various machining condition and cutting speeds.

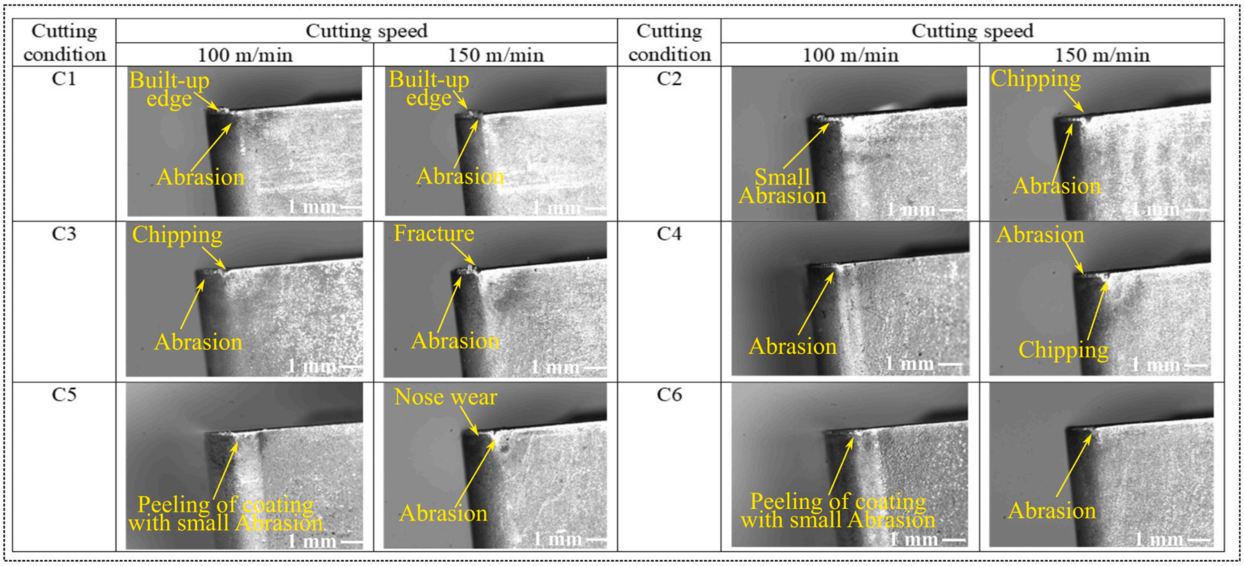

Fig. 5. Tool wear observed under different cutting conditions.

the attached material is taken off, it removes the tool material, which results in chipping off the cutting edge. The study revealed the leading cutting edge to be in a fracture-like condition at a higher cutting speed [57]. However, because of the efficient tribo layer generated in the cutting zone, it was thought that the hBN + MoS_2 nanofluids had avoided the production of higher flank wear by delaying the creation of a built-up layer [56]. Additionally, it has resulted in tool chipping at 150 m/min. Peeling off and abrasive wear of the tool during cryogenic conditions is more severe than in other machining conditions. Furthermore, this is further accelerated by a higher cutting speed. With the increased friction between the tool and workpiece over time, cryogenic cooling is expected to result in higher abrasive wear than hybrid nanofluid.

3.1.2. Surface roughness

In machining operations, lower surface roughness in machined components is highly preferred as it impacts the machined workpiece's thermal, electrical, and mechanical properties and can be considered to define the quality of the machined surface. The cutting parameters, coolants, and application methods are critical in achieving the desired surface finish. A suitable cutting speed and low feed rate is one approach, but a low feed rate is not the best method as it increases process time and reduces production. This is why a cooling/lubrication process is typically used during machining. The technique to be employed must be both clean and sustainable, as well as highly effective. As a result, it is necessary to analyze the variation in surface roughness under various sustainable strategies such as MQL, vegetable oil-based MQL, and nanofluid-MQL with selected cutting parameters. With fixed feed rate and depth of cut, the experiments were carried out at two different cutting speeds: 100 and 150 m/min under C1 to C6 machining conditions. Accelerating

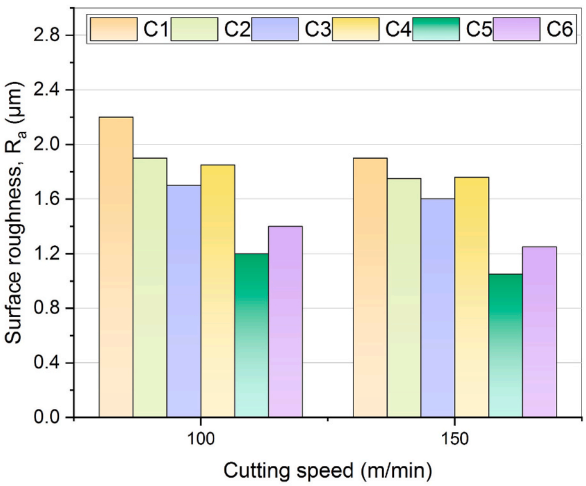

Fig. 6. Comparison of surface roughness resulting under various machining conditions.

the cutting speed from 100 to 150 m/min is believed to soften the material and result in easy cutting. It is observed from the comparison of Ra presented in Fig. 6 that minimum surface roughness resulted under the C5 condition, and maximum surface roughness is resulted in dry machining (C1). The increased cutting speed lowered the vibrations and reduced surface roughness while machining. A recent study reported cutting speed as a significant parameter affecting vibration and concluded that increased cutting speed reduced the vibration and surface roughness [3]. The efficient heat control under MQL and hybrid nanofluid-MQL resulted in an improved surface finish by avoiding the adhesion of workpiece material to the tool cutting edge. The thermal distortion caused by excessive heat and rapid tool wear drives poor surface finish under dry machining [52]. The enhanced thermal conductivity of the nanofluids with the presence of MoS_2 and hBN, the presence of the oil-film layer in machining interfaces, and improvement in tribological conditions are responsible for the improved surface finish under C5. This is attributed to the reduction in thermal softening of the tool materials and the reduction in built-up edge formation during machining with nanofluids, as reported [12].

In the hybrid nanofluid, the hBN structure is spherical, and MoS_2 is layered. This nanofluid is believed to produce more potent mending, polishing, rolling, and interlayer sliding action mechanisms. Comparable outcomes were demonstrated by improved surface finish when Inconel alloys were machined using graphene and hBN-based nanofluids [56]. MoS_2 and hBN have been utilized as solid lubricants due to their low coefficient of friction. The boron and nitrogen atoms in hBN are firmly bound to one another on the same layer, these layers adhere to the contact surfaces and slide over one another, which is thought to help create a better surface topography [58]. At 100 m/min, the Ra value varies from 2.2 μm (C1) to 1.2 μm (C5) and 1.9 μm (C1) to 1.05 μm (C5) at 150 m/min. The improvement in Ra at 150 m/min under the C5 condition, compared to other conditions, is 45 % (C1), 39 % (C2), 34 % (C3), 40 % (C4), and 16 % (C6). The application of LCO_2 provided the benefit of improved cooling and protection of the tool cutting edge from softening, which has further reduced the friction and produced a better surface finish in contrast to dry, flood, and MQL environments. Similar observations were reported by applying LCO_2, and the surface roughness was reduced by around 8–41 % and 1–18 % while turning Ti–6Al–4V and Inconel 718 [59].

3.1.3. Power consumption

The study of power utilized can support understanding the energy requirements of the machining operation. To meet sustainable manufacturing goals, the amount of power used during machining needs to be minimized [60]. The machine tool, accessories, and cooling system consumed power during machining. Fig. 7 compares power consumed during machining under various cutting conditions. Dry machining without any usage of a coolant supply system consumed lower power. The cutting fluid is pumped externally to the rake face during machining in flood cooling. The power required for machining and the fluid pump can then be added to determine the total power for flood cooling. The power consumed in running fluid pump during flood cooling resulted in higher power consumption than dry machining. Using an air compressor to apply the compressed air during lubricant delivery in MQL further resulted in higher power consumption in MQL (C3). However, it is evidenced that the improvement in machining performance with hybrid-MQL and LCO_2 (C5 and C6) resulted in lower power consumption than pure MQL applications. During the application of LCO_2, no external source is utilized apart from the cylinder to supply LCO_2. Therefore, the power consumption in C6 is less than in flood and MQL conditions. At the same time, efficient cooling offered by LCO_2 decisively reduces heat, friction at the cutting zone, and tool-chip contact length, reducing power consumption. Further, it has been observed from the comparison that an increase in cutting speed from 100 to 150 m/min caused higher power consumption due to increased power requirement to rotate the spindle at higher rpm.

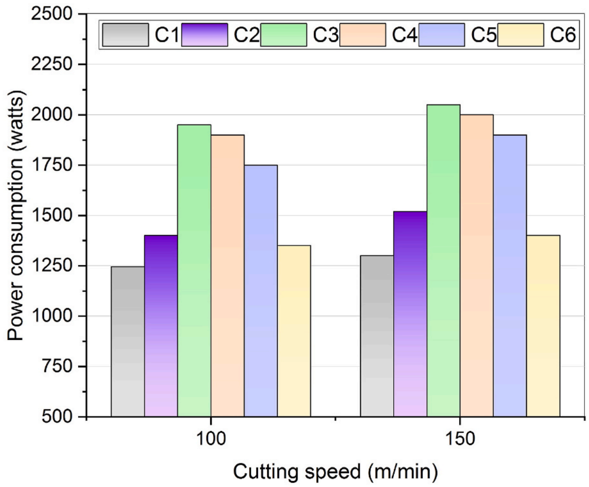

Fig. 7. Comparison of power consumption under various machining conditions.

3.2. Sustainability assessment

3.2.1. Economic assessment

Economic assessment is vital in machining operations, encompassing financial considerations and sustainability factors. By assessing the cost-effectiveness of machining processes, manufacturers can identify opportunities to minimize waste, enhance resource efficiency, and decrease their environmental footprint. Such measures may involve reducing energy usage, minimizing material waste, and implementing recycling initiatives. By integrating sustainability considerations into their economic assessment, manufacturers can not only reduce costs but also contribute to the long-term well-being of the planet [2]. In summary, economic assessment is a pivotal tool for manufacturers striving to achieve a harmonious balance between profitability and sustainability in their machining operations.

In the present study, an economic assessment was conducted to compare six different cutting environments, considering two cutting velocities (100 m/min and 150 m/min), to find a sustainable parameter and novel results for working on Nimonic 80 workpieces, a nickel-based material. The analysis here and the following subsections is based on the works and models developed in previous studies [47,59]. Fig. 8 illustrates the various factors involved in the assessment.

3.2.1.1. Cost for machining ($C_{total\ machining}$). The total machining cost for turning a Nimonic 80 workpiece under different environments (C1, C2, C3, C4, C5, C6) is determined by various factors that impact it, ranging from machine setup to post-processing. These factors are further broken down into unit components, which collectively provide an estimation of the overall cost of machining any workpiece. All our cost formulas are calculated based on the cost of machining a single unit per hour ($/hr), using 1 h as a reference for simplified and convenient calculations. The unit components in the machine setup include machine tool and labor cost (C_{lmt}), while the cutting process involves unit components such as cutting fluid cost (C_{cf}), cutting tool cost (C_{ct}), and power consumption cost (C_{power}). Additionally, post-processing unit components encompass waste processing and management cost (C_{waste}). The overall cost of machining a workpiece can be obtained by summing up all the unit components, as depicted by equation (1).

$$C_{total\ machining} = C_{lmt} + C_{cf} + C_{ct} + C_{power} + C_{waste} \tag{1}$$

Where,

$C_{total\ machining}$ = Total machining cost ($)
C_{lmt} = Labour and machine tool utilization cost ($)
C_{cf} = Cutting fluid utilization cost ($)
C_{ct} = Cutting tool cost ($)
C_{power} = Power consumption cost ($)
C_{waste} = Wast management and processing cost ($)

3.2.1.2. Labour and machine-tool utilization cost (C_{lmt}). The expenses related to labor, taxes, maintenance, and machine tools are crucial and interconnected factors in the operation of machinery. The labor wages are primarily determined by the level of expertise and skills necessary for operating a particular setup. The setup cost for dry operations is lower since it doesn't require additional components compared to setups such as C2, C3, C4, C5, and C6. Consequently, complex setups like those shown in Table 3 exhibit an increase in the overall machine setup and labor costs.

3.2.1.3. Cutting fluid utilization cost (C_{cf}). The utilization of cutting fluid holds significant importance in machining, as it effectively reduces heat generated during cutting and is a preventative measure against tool wear. This is achieved by creating a barrier between the tool and the chips being removed, thus preventing direct contact. The utilization of recently developed cooling/lubrication

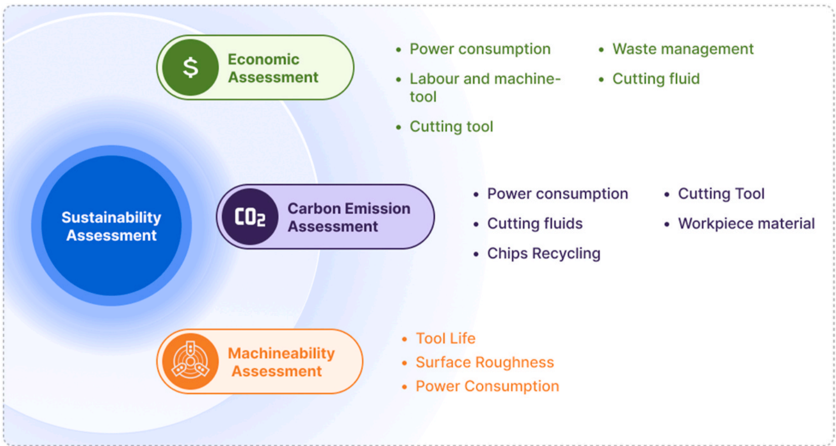

Fig. 8. Aspects of sustainability assessment.

Table 3
Machine-tool usage and labour costs.

	Component	C1	C2	C3	C4	C5	C6
Machine tool usage	Machine Tool Investment ($) [A]	22500.00	22500.00	22500.00	22500.00	22500.00	22500.00
	Investment for tooling (3 % of (A)) ($) [B]	675.00	675.00	675.00	675.00	675.00	675.00
	Investment for coolant delivery system ($) [C]	0.00	0.00	3180.00	3180.00	3180.00	675.00
	Investment for machine-tool installation ($) [D]	55.00	55.00	55.00	55.00	55.00	55.00
	Total ($) ([A] + [B] + [C] + [D])	23230.00	23230.00	26410.00	26410.00	26410.00	23905.00
	Depreciation Period (a)	10.00	10.00	10.00	10.00	10.00	10.00
	Cost rate of maintenance (1.5 % of A + B + C)	347.63	347.63	395.33	395.33	395.33	357.75
	Cost of insurances/taxes (0.4 % of A + B + C)	92.70	92.70	105.42	105.42	105.42	95.40
	Cost for tool holder ($)	24.00	24.00	24.00	24.00	24.00	24.00
	Time fraction for usage (h/a)	2808.00	2808.00	2808.00	2808.00	2808.00	2808.00
	Down time fraction [%]	20.00	20.00	20.00	20.00	20.00	20.00
	Time fraction for actual usage (h/a)	2246.40	2246.40	2246.40	2246.40	2246.40	2246.40
	Cost rate for machine tool usage ($/h)	1.24	1.24	1.41	1.41	1.41	1.28
Labor	Cost rate for direct labor ($/h) [V]	6.00	6.00	6.00	6.00	6.00	6.00
	Cost rate for indirect labor [10 % of V] ($/h)	0.60	0.60	0.60	0.60	0.60	0.60
	Cost rate for supervision [12 % of V] ($/h)	0.72	0.72	0.72	0.72	0.72	0.72
	Cost rate for fringe benefits [33 % of V] ($/h)	1.98	1.98	1.98	1.98	1.98	1.98
	Cost rate for Operator ($/h)	9.30	9.30	9.30	9.30	9.30	9.30
Overall Cost	Cost of overall machining ($/h)	10.54	10.54	10.71	10.71	10.71	10.58

techniques has emerged as a crucial focus in the pursuit of sustainable machining [2]. In the present study, six distinct lubrication/cooling techniques were employed to investigate the behavior of Nimonic 80 workpieces at two different cutting speeds.

The cutting lubricant fluid components considered in this study are as follows.

1. CLF Concentrate (Volumetric) Price ($/l): The cost per liter of concentrated cutting fluid (CLF) used to facilitate cutting and cooling during the machining process.
2. CLF Disposal with Phase Separation Price ($/l): The cost per liter for disposing of used cutting fluid after phase separation, a process that separates contaminants for proper disposal.
3. Volume Fraction of CLF [%]: The percentage of cutting fluid used relative to the total volume of the cutting fluid mixture during machining.
4. Volume of CLF Needed (l): The total volume of cutting fluid required for the machining process.
5. Volume of CLF Concentrate Needed (l): The specific volume of concentrated cutting fluid required to create the desired cutting fluid mixture.
6. Cost of CLF Concentrate ($): The total cost of the concentrated cutting fluid needed for the machining process.
7. Disposal Cost of CLF ($): The total cost of disposing of used cutting fluid after phase separation.
8. Costs of Maintenance and Labour ($): The expenses associated with maintaining and managing the cutting fluid system, including labor costs.
9. Cost of Overall CLF ($): The overall cost of the cutting fluid system, including the cost of CLF concentrate, disposal, maintenance, and labor expenses.
10. Lifetime of Cutting Fluid (h): The duration that the cutting fluid remains effective and functional during machining before requiring replacement.
11. Non-Returnable CLF Usage (l/min): The rate at which non-returnable cutting fluid is consumed during the machining process, measured in liters per minute.

Table 4
Cutting fluid consumption cost.

Component	C1	C2	C3	C4	C5	C6
CLF concentrate (volumetric) price ($/l)	0.00	7.00	6.25	35.00	38.75	0.38
CLF disposal with phase separation price ($/l)	0.00	0.15	0.00	0.00	0.00	0.00
Volume fraction of CLF [%]	0.00	5.00	100.00	100.00	100.00	0.00
Volume of CLF needed (l)	0.00	75.00	0.20	0.20	0.20	50.00
Volume of CLF concentrate needed (l)	–	4.82	–	–	–	–
Cost of CLF concentrate ($)	–	36.52	15.00	15.00	15.00	–
Disposal cost of CLF ($)	–	15.33	–	–	–	–
Costs of maintenance and labour ($)	–	0.18	–	–	–	–
Cost of overall CLF ($)	–	56.85	15.00	15.00	15.00	–
Lifetime of cutting fluid (h)	–	470.00	6048.00	6048.00	6048.00	–
Non-returnable CLF usage (l/min)	–	–	0.0005	0.0005	0.0005	1.00
Cost of non-returnable CLF specific usage ($/l)	–	–	3.00	3.00	3.00	0.12
CLF usage cost rate ($/h)	0.00	0.12	0.09	0.09	0.09	7.20

12. Cost of Non-Returnable CLF Specific Usage ($/l): The cost per liter of non-returnable cutting fluid utilized during the machining process.
13. CLF Usage Cost Rate ($/h): The cost per hour associated with the overall usage of cutting fluid during the machining process. These components are vital for understanding the costs and volumes involved in using cutting fluid in machining operations, and they contribute to a comprehensive analysis of the cutting fluid's impact on the process. The calculation of cutting lubricant fluid (CLF) utilized during machining using all the above-mentioned components is shown in Table 4.

3.2.1.4. Power consumption cost (C_{power}). In the pursuit of sustainability, the role of power consumption cost in machining is paramount. As global environmental awareness grows, the significance of minimizing energy usage and its related expenses has escalated [47]. Power consumption represents a substantial portion of the overall costs in machining operations. By optimizing power consumption, manufacturers can decrease expenditures and take significant contributions to sustainability by conserving energy resources and curbing carbon emissions [2].

During the study, the average apparent power consumption was measured while turning Nimonic 80 at two different speeds under various cutting conditions. To estimate the costs, a standard power tariff of $0.21 per kilowatt-hour (kWh) was applied [47]. The C_{power} vales were calculated using equation (2) given below.

$$C_{power} = C_{power\ tariff} \times P_{total\ power\ consumed} \tag{2}$$

where,

$C_{power\ tariff}$ = Cost of power tariff $\left(\frac{\$}{KWh}\right)$.

$P_{total\ power\ consumed}$ = Total power consumed during machining (kwh).

The cost for power consumption (C_{power}) was found out to be more for C1 (for100 m/min) and C4 (for 150 m/min) among all different cutting environments.

3.2.1.5. Cost of cutting tool (C_{ct}). The cutting tool plays an important role in any machining process as it influences both tool life and the surface quality of the workpiece. The economic aspects of the machining process are affected by the cutting tool life. Therefore, selecting a tool with higher tool life, geometry, and coating is essential. In this study, PVD-TiAlN-coated carbide inserts were employed. The machining of Nimonic 80 workpieces was conducted using the same cost-cutting tool under various cutting conditions. The cutting tool cost has been determined by comparing tool life under different conditions. A standard condition was considered in which a tool wear of 0.3 mm was applied over the shortest period of time to perform a comparison analysis. The resultant values represent the cost of cutting tool.

3.2.1.6. Waste management and processing cost (C_{waste}). Effective waste management and processing play a crucial role in achieving sustainability objectives. As manufacturing industries work towards minimizing their environmental footprint, recognizing the significance of waste management and processing expenses becomes imperative. Implementing proper waste management practices mitigates adverse environmental effects, offers potential cost savings, and optimizes resource utilization. In the context of the current study, the waste components encompass chip waste, cutting tools, cutting fluids, and undesired materials left after machining (swarf), as documented in the literature [61]. The calculation incorporates the labor cost of India. The calculation of waste processing and management is shown in Table 5. Table 6 shows the final calculated values of all components of economic assessment.

Once all the cost components have been determined for machining Nimonic 80 under six different cutting environments at two speeds, equation (1) can be utilized to calculate the total cost of machining. The comparison of machining costs for the Nimonic 80 workpiece across the various cutting environments and speeds is illustrated in Fig. 9. Table 6 presents the considered cost components, and by summing up these elements, $C_{total\ machining}$ can be obtained. From an economic standpoint, machining at 150 m/min proves more favourable than machining at 100 m/min across all cutting environments. The total machining costs exhibit a decrease of 6.1 %, 34.5 %, 33.6 %, 35.6 %, 33 %, and 36.4 % for C1, C2, C3, C4, C5, and C6 cutting environments, respectively, when comparing machining at 150 m/min to 100 m/min. Among all machining conditions and speeds, utilizing the hybrid vegetable oil-based nanofluid-MQL cutting environment proves economically viable compared to other cutting environments. In terms of cost contribution to $C_{total\ cutting}$, C_{ct} was the major factor in this study, followed by C_{lmt}.

Table 5
Calculation of waste processing and management cost.

	Component	C1	C2	C3	C4	C5	C6
Swarf	CLF separation cost ($)	0.0000	0.0110	0.0110	0.0110	0.0110	0.0000
	Preparation cost ($)	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040
	Swarf preparation cost per produced part ($)	0.0040	0.0150	0.0150	0.0150	0.0150	0.0040
Energy	Energy Cost ($)	0.0032	0.0032	0.0030	0.0030	0.0030	0.0000
	Labor Cost ($)	0.0025	0.0025	0.0025	0.0025	0.0025	0.0000
	Cleaning Emulsion Costs ($)	0.0000	0.0060	0.0040	0.0040	0.0040	0.0000
	Part cleaning cost ($)	0.0100	0.0100	0.01000	0.0000	0.0000	0.0000
Total	Total cleaning cost per part ($)	0.0100	0.0300	0.02000	0.0200	0.0200	0.0000

Table 6
Total cost of machining operation.

$v_c = 100$ m/min						
	C1	C2	C3	C4	C5	C6
C_{lmt} ($)	1.054	1.054	1.071	1.071	1.071	1.058
C_{cf} ($)	0.000	0.012	0.009	0.009	0.009	0.720
C_{ct} ($)	6.250	4.680	3.409	3.750	2.710	3.125
C_{power}($)'	0.079	0.060	0.066	0.073	0.042	0.047
C_{waste} ($)	0.010	0.027	0.025	0.015	0.015	0.004
$C_{total\ cutting}$ ($) (2)	7.392	5.833	4.580	4.918	3.847	4.954
$v_c = 150$ m/min						
	C1	C2	C3	C4	C5	C6
C_{lmt} ($)	0.610	0.610	0.630	0.630	0.630	0.620
C_{cf} ($)	0.000	0.007	0.005	0.005	0.005	0.420
C_{ct} ($)	6.250	3.125	2.300	2.430	1.900	2.080
C_{power}($)	0.069	0.052	0.079	0.088	0.028	0.028
C_{waste} ($)	0.010	0.027	0.025	0.015	0.015	0.004
$C_{total\ cutting}$ ($) (2)	6.939	3.821	3.039	3.168	2.578	3.152

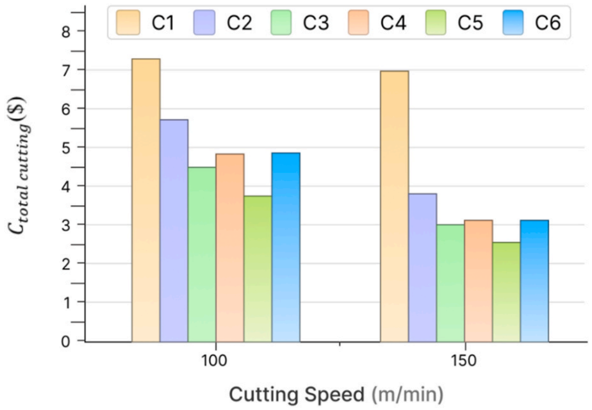

Fig. 9. Total machining cost.

3.2.2. *Carbon emissions assessment* (CE_{total})

In today's era of heightened environmental awareness, understanding the impact of carbon emissions in machine operations is crucial. Valuable insights into their environmental consequences can be gained by thoroughly examining the carbon emissions generated during these processes. This assessment allows us to identify areas needing improvement, foster the adoption of sustainable practices, and contribute positively to a greener future [62]. In the present work, the main contributors to carbon emissions in CNC-based machining of Nimonic 80 are identified as the cutting tool, cutting fluid, workpiece, electricity consumption, and chip recycling. To determine the carbon footprints during CNC machining of Nimonic 80 at various speeds under different cooling/lubrication conditions, equation (3) is employed.

$$CE_{total} = CE_{power} + CE_{ct} + CE_{cf} + CE_{material} + CE_{cr} \quad (3)$$

Where,

CE_{total} = Total carbon emission from CNC machining (kg CO_2)
CE_{power} = Carbon emissions from power consumption of operating machine (kg CO_2)
CE_{ct} = Carbon emissions from cutting tool (kg CO_2)
CE_{cf} = Carbon emissions from cutting fluids (kg CO_2)
$CE_{material}$ = Carbon emissions from workpiece material (kg CO_2)
CE_{cr} = Carbon emissions from chips recycling (kg CO_2)

During the estimation of carbon emissions while machining the Nimonic-80 workpiece, the following assumptions and guidelines were followed.

1. The carbon emissions resulting from the extraction, primary production, and fabrication of Nimonic-80 were not considered.
2. Emissions released during in-process transportation were not considered.

3. Carbon dioxide (CO_2) is naturally present in the environment and is compressed into cylinders for storage and released back into the environment during machining operations. Therefore, carbon emissions from liquid CO_2 (LCO_2) were not considered as they are assumed to be a direct by-product of the environment.
4. The carbon footprint of each cooling/lubrication environment was determined until each machining process reached the criteria of tool wear or failure.
5. The specific environmental impact of the cutting tool was not considered due to the lack of appropriate datasets, which decreases the scientific validity of the study and underscores the need for developing datasets related to machining. However, it is essential to note that this emission factor does not affect the conclusions of the study.

3.2.2.1. Carbon emissions from power consumption of operating machine (CE_{power}). CNC machining is a manufacturing process involving computer numerical control (CNC) machines to produce parts and components. These machines consume energy and emit carbon into the atmosphere, contributing to global warming [63]. Carbon emissions released from this factor can be found using equation (4) [47]. The energy consumed during machining is calculated using equation (5).

$$CE_{power} = CEF_{power} \times EC_{machining} \tag{4}$$

$$EC_{machining} = \int_0^{T_{am}} P_{am} dt + \int_0^{T_{airm}} P_{airm} dt + \int_0^{T_{sbm}} P_{sbm} dt \tag{5}$$

Where,

CEF_{power} = Carbon emission factor of power consumption (kg CO_2/kWh)
$EC_{machining}$ = Energy consumed during machining (kWh)
P_{am} = Power consumed during actual machining operation (kW)
P_{airm} = Power consumed during air-cut operating mode (kW)
P_{sbm} = Power consumed during standby mode (kW)
T_{am} = Time consumed during actual machining operation (h)
T_{airm} = Time consumed during air-cut operating mode (h)
T_{sbm} = Time consumed during standby mode (h)

As per power grid system, Carbon emission factor of power consumption is taken average of 0.72 kg CO_2/kWh [64,65]. The carbon emissions produced due to the power consumption while turning Nimonic 80 under different cooling/lubrication environments can be seen in Table 7. The carbon footprint values were measured until the tool reached tool wear criteria or failure for all environments. The CE_{power} while turning at 100 m/min is higher than at 150 m/min for all six cooling environments by the following percentages: 2.07 % (C1), 0.2 % (C2), 1.2 % (C3), 0.45 % (C4), 2.19 % (C5), 0.84 % (C6) respectively. In the current study, a noticeable difference of CE_{power} between each cutting environment was seen as for 100 m/min cutting speed as compared to C1, with increase in 2.6 % (C2), 9.9 % (C2), 8 % (C3), 12.7 % (C4), 6.4 % (C5) respectively. Similarly, for 150 mm/min, as compared to C1, increases in 4.5 % (C2), 10.8 % (C2), 9.8 % (C3), 12.5 % (C4), 7.8 % (C5) can be observed. The value of CE_{power} for hybrid nano-MQL was found to be the highest for both speeds.

3.2.2.2. Carbon emissions from cutting tool (CE_{ct}). Understanding and quantifying carbon emissions is crucial for identifying areas of improvement and implementing sustainable practices. One area that contributes to carbon emissions is the use of cutting tools in various industries. Monitoring and measuring carbon emissions released from cutting tools can help assess their environmental impact and promote eco-friendly alternatives [66]. Here, carbon emissions from cutting tool utilization are evaluated using equation (6) [62]. And the Carbon emissions factor of cutting tool is calculated using equation (7).

Table 7
Carbon emission values.

		CE_{power} (kg CO_2)	CE_{ct} (kg CO_2)	CE_{cf} (kg CO_2)	$CE_{material}$ (kg CO_2)	CE_{cr} (kg CO_2)	CE_{total} (kg CO_2)	CE_{total} With time reference (kg CO_2)
v_c = 100 m/min	C1	1.71	0.26	0	4.40	0.10	6.47	3.77
	C2	1.75	0.24	0.025	5.87	0.14	8.02	3.51
	C3	1.88	0.22	0.00015	8.07	0.19	10.36	3.29
	C4	1.8	0.23	0.00014	7.33	0.17	9.59	3.35
	C5	1.92	0.19	0.00025	10.64	0.24	13.00	3.13
	C6	1.82	0.22	0	8.806	0.205	11.05	3.22
v_c = 150 m/min	C1	1.67	0.25	0	3.86	0.09	5.81	5.81
	C2	1.75	0.22	0.023	7.7364	0.18	9.91	4.95
	C3	1.85	0.23	0.00013	10.49	0.24	12.83	4.72
	C4	1.83	0.24	0.00012	9.9468	0.23	12.25	4.76
	C5	1.88	0.12	0.00023	12.70	0.29	15.01	4.56
	C6	1.80	0.16	0	11.60	0.27	13.84	4.61

$$CE_{ct} = CEF_{ct} \times M_{ct} \times \left(T_{am} / T_{tool\ life} \right) \tag{6}$$

Where,

CE_{ct} = Carbon emissions from cutting tool utilization (kg CO_2)
CEF_{ct} = Carbon emissions factor of cutting tool (kg CO_2/kWh)
T_{tool} = Tool life (min)
T_{am} = Time consumed during actual machining operation (h)
M_{ct} = Mass of cutting tool (kg)
Also [67].

$$CEF_{ct} = CEF_{electricity} \left(E_{ctm} / M_{ct} \right) \tag{7}$$

Where,

$CEF_{electricity}$ = the carbon emission factor from electricity consumption for cutting tool production
E_{ctm} = Embodied energy of cutting tool material
M_{ct} = Mass of cutting tool (kg)

The cutting edge was replaced without being reused by resharpening as soon as the predetermined tool wear condition was met. According to the methodology outlined in the literature [62,68], the carbon emissions factor for the cutting tool is calculated as 31.6 kg-CO_2/kg. The carbon emission footprint values for CE_{ct} can be seen in Table 7**.** The CE_{ct} while turning at 100 m/min is higher than at 150 m/min for all 6 cooling environments by 2.9 % (C1), 7.14 % (C2), −4.32 % (C3), −3.2 % (C4), 2.19 % (C5), 0.84 % (C6) respectively. In current study, a noticeable difference of CE_{ct} between each cutting environment was seen for 150 m/min cutting speed as compared to C1, decrease in 11.2 % (C2), 7.3 % (C2), 4.34 % (C3), 52.2 % (C4), 34.2 % (C5) was seen respectively. Similarly, for 100 mm/min, as compared to C1, decrease in 7.14 % (C2), 14 % (C2), 10 % (C3), 25.7 % (C4), 13.7 % (C5) was observed, respectively. The value of CE_{ct} for dry (C1) was the highest for both speeds.

3.2.2.3. Carbon emissions from cutting fluids (CE_{cf}). Cutting fluid is a crucial element of the CNC machining process since it aids in cooling and lubricating the cutting tool and workpiece, enhancing the surface quality and extending the tool life. However, the production, use, and disposal of cutting fluid can contribute to carbon emissions. When assessing the total carbon footprint of a CNC machining system, it is crucial to include carbon emissions from cutting fluid [69]. To calculate carbon footprints from cutting fluid utilization, the carbon emission factor of that specific cutting fluid is to be multiplied by the quantity of fluid being used. For the LCO_2 environment, the emissions released will be null as CO2 is obtained as a direct by-product extracted from nature [5]. Here, carbon emissions from cutting fluid are evaluated using the following equations (8)–(10) [67]:

$$CE_{cf} = \left((T_{am} + T_{sbm}) / \ T_{coolant} \right) \times (CE_{oil} + CE_{wd}) \tag{8}$$

$$CE_{oil} = CEF_{oil} \times (V_{ic} + V_{ac}) \tag{9}$$

$$CE_{wc} = CEF_{wc} \times \frac{[(V_{ic} + V_{ac})]}{\delta} \tag{10}$$

Where,

$T_{coolant}$ = Replacement cycle of coolant (h)
CEF_{oil} = Carbon emission factor for production of cutting fluid (kg CO_2/L)
CEF_{wd} = Carbon emission factor for waste disposal of cutting fluid (kg CO_2/L)
V_{ic} = Initial volume of cutting fluid (L)
V_{ac} = Additional volume of cutting fluid (L)
δ = Predetermined cutting fluid concentration

In general, C3, C4, C5 approach uses a minimal amount of oil and water; thus, work of cleaning, recycling and disposal is minimal and hence, their $CE_{waste\ disposal}$ is not considered for them [70]. Now the value of CEF_{oil} for C2 is 2.87 kg CO_2/L [67,71], for C3 is 4.79 kg CO_2/L, C4 is 4.91 kg CO_2/L [72,73], C5 is 5.51 kg CO_2/L [73] The value of CEF_{wd} for C2 is 0.2 kg CO_2/L [74] Coolant replacement time for C2 is taken to be a 2-month time period as industrial standard [75].

3.2.2.4. Carbon emissions from workpiece material ($CE_{material}$). While machining, the cutting tool reshapes the workpiece, generating chips as some of the material is transformed. The rest of the material moves forward to be used in producing semi-finished or finished products. It is crucial to emphasize the importance of considering carbon emissions solely related to producing the material that becomes chips. Thus, when calculating carbon emissions for the system, the focus lies on quantifying and accounting for the emissions produced while manufacturing the removed material. This can be accomplished by employing the following equation (11) [64]. The Carbon emission factor of workpiece material can be calculated using equation (12).

$$CE_{material} = \left(CEF_{material} \times M_{chips}\right) \tag{11}$$

$$M_{chip} = \rho \times \sigma \times T_{am}/10^6 \tag{12}$$

Where,

$CEF_{material}$ = Carbon emission factor of workpiece material (kg CO_2e/kg)

M_{chips} = Carbon emission factor of workpiece material (kg)

ρ = Density of material (kg/m^3)

σ = Material removal rate (mm^3/min)

Extensive research has been conducted to determine the embodied energy of various materials; however, a standardized approach for calculating the carbon intensity of different materials is lacking. As a result, this study adopts a methodology that converts the embodied energy of materials into their standard coal equivalent. By leveraging the carbon intensity of coal, the Carbon Emission Factor (CEF) for different materials can be derived. Table 8 presents the carbon emission factor values obtained by considering the embodied energy of the materials. Table 7 provides the carbon footprints released due to $CE_{material}$. Equation (13) provided below is utilized for calculating the $CEF_{material}$ [74].

$$CEF_{material} = \left(EE_{coal\ equivalent} \times CEF_{coal\ equivalent}\right) \tag{13}$$

Where,

$EE_{coal\ equivalent}$ = Standard coal equivalent of the material's embodied energy (kg SCE/kg)

$CEF_{coal\ equivalent}$ = Carbon emission factor of coal (kg CO_2/kg ce)

3.2.2.5. Carbon emissions from chips recycling (CE_{cr}). Given the evolving nature of the manufacturing industry, it has become increasingly important to identify and address carbon emissions sources across the production cycle. A particular area of focus is the recycling of chips generated during machining operations [68,76]. Chip recycling is commonly employed to recover materials. The specific recovery technology and criteria may vary depending on the type of scraps involved (e.g., iron scrap, steel scrap, aluminum scrap, etc.), leading to varying energy consumption and carbon emissions during the recycling process. Table 8 provides the carbon emission factor for recycled waste Nimonic 80 chips. Table 7 provides the carbon footprints released due to CE_{cr} and can be calculated using equation (14). The determination of CEF_{cr} is based on its standard coal equivalent, as demonstrated below in equation (15).

$$CE_{cr} = \left(CEF_{cr} \times M_{chips}\right) \tag{14}$$

$$CEF_{cr} = \left(EC_{ce} \times CEF_{ce}\right) \tag{15}$$

Where,

EC_{ce} = The amount of standard coal consumed in the recycling process of a unit mass of scrap. (kg SCE/kg)

CEF_{cr} = The carbon emission factor of waste Nimonic 80 scrap (kg CO_2/kg)

After determining the emission components for machining Nimonic 80 under six different cutting environments at two speeds, the overall carbon emissions of the machining operation can be calculated using equation (3). Since emission values for specific times were unavailable, they were determined for the entire machining time of each cutting environment. To ensure a fair comparison, the lowest tool life of 3.5 min was used as a reference to calculate the total carbon emissions CE_{total}. The emissions for the Nimonic 80 workpiece across the various cutting environments and speeds are depicted in Fig. 10. Table 7 presents the cost components considered and summing up these elements' yields CE_{total}. From an environmental perspective, machining at 100 m/min is more favourable than machining at 150 m/min across all cutting environments. Comparing machining at 150 m/min to 100 m/min, CE_{total} shows an increase of 55.8 %, 41.1 %, 43.4 %, 42 %, 45.5 %, and 43.1 % for C1, C2, C3, C4, C5, and C6 cutting environments, respectively. Among all machining conditions and speeds, utilizing the hybrid vegetable oil-based nanofluid-MQL cutting environment proves economically viable compared to other cutting environments. For a cutting velocity of 100 m/min, compared to C1, a decrease in carbon emission value of 6.9 %, 12.6 %, 11.1 %, 16.83 %, and 14.6 % can be observed for C2, C3, C4, C5, and C6 cutting environments, respectively. Similarly, for a cutting velocity of 150 m/min, a decrease in carbon emission value of 15.7 %, 19.6 %, 18.9 %, 22.3 %, and 21.5 % can be observed for C2, C3, C4, C5, and C6 cutting environments, respectively. Utilizing hybrid nanoparticles can considerably enhance surface quality while lowering production costs and CO_2 emissions [70].

4. Conclusions

The study investigated different lubricating and cooling methods, such as dry, flood, MQL, hybrid nanofluid-MQL, and LCO_2, to assess their technological performance, economic viability, and environmental impact. The machining sector can use the outcomes in making informed decisions regarding the most suitable cooling and lubricating methods for promoting sustainable development. The outcomes of the study are as follows.

- High cutting speeds result in decreased tool life due to the generation of high temperatures. Due to heat-related wear mechanisms, dry cutting exhibits the shortest tool life and highest flank wear. The low thermal conductivity of Nimonic 80 contributes to

Table 8
Carbon emission factor of material and chips recycling.

Material	Embodied energy (MJ/kg)	Standard coal Equivalent (EC_{ce}) [5]	$CEF_{coal\ equivalent}$ (kg CO_2/kg ce) [74]	CEF_{cr} (kg CO_2/kg)
Nimonic 80	219.000	7.460	2.470	18.420
Waste Nimonic 80 scrap	5.078	0.173	2.470	0.430

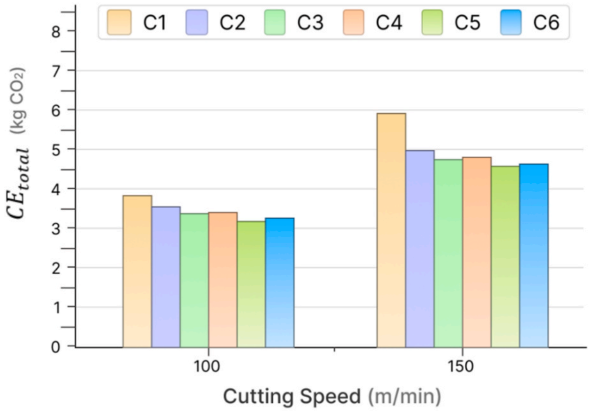

Fig. 10. Total carbon emissions from machining.

reduced tool life. However, cooling/lubrication methods such as flood and minimum quantity lubrication (MQL) reduce tool wear. The hybrid nanofluid-MQL condition demonstrates the extended tool life. Cutting speed from 100 to 150 m/min has shown a reduction in tool life across different conditions by 42 % (C1), 13 % (C2), 14 % (C3), 10 % (C4), 21 % (C5), and 13 % (C5). The results demonstrate significant improvements in tool life under the hybrid nanofluid-MQL condition at 100 m/min as: 59 % (C1), 45 % (C2), 24 % (C3), 31 % (C4), and 17 % (C6). Cryogenic cooling caused higher abrasive wear, particularly at higher cutting speeds. The use of nanofluids and the formation of a tribo-film layer help decrease friction and tool wear.

- The comparison of surface roughness (Ra) indicated that the C5 condition yields the minimum surface roughness, while dry machining (C1) results in the maximum surface roughness at both cutting speeds. The utilization of MQL and hybrid nanofluid-MQL cooling/lubrication techniques enhance surface finish by preventing workpiece material adhesion to the cutting tool edge and effectively controlling heat. The application of LCO_2 reduced micro-chip residue from diffusing on cutting edge improved surface quality. Combining MoS_2 and hBN nanoparticles in hybrid nanofluids offers superior lubrication and results in a better surface finish compared to other conditions.
- The unique spherical shape of hBN and the layered structure of MoS_2 contribute to its high thermal stability and friction reduction capabilities. The application of MoS_2+hBN nanofluids delays the formation of built-up-edge and layers, preventing rapid flank wear and resulting in lower flank wear.
- Different machining methods consume varying power levels, with dry machining being the least power-intensive. Flood cooling with an external pump and MQL with air compressor usage result in higher power consumption. However, hybrid-MQL and LCO_2 applications exhibit improved performance and lower power consumption. Increasing cutting speed from 100 to 150 m/min leads to higher power requirements by 3.85 % (C1), 9.84 % (C2), 4.88 % (C3), 6.25 % (C4), 7.90 % (C5), and 5.18 % (C6).
- Additionally, an economic assessment was conducted in this study to compare six different cutting environments and two cutting velocities (100 m/min and 150 m/min) for machining Nimonic 80 workpieces. Decreased machining costs ranging from 6.1 % to 36.4 % were found while machining at 150 m/min, making it more economically favourable than at 100 m/min across all cutting environments. The hybrid vegetable oil-based nanofluid-MQL cutting environment was identified as the most economically viable option. Cutting tool cost (C_{ct}) played a significant role in the overall machining cost, followed by labor and machine-tool utilization (C_{lmt}). This economic assessment is crucial for manufacturers seeking to balance profitability and sustainability in their machining operations.
- The results indicate that machining at 100 m/min is more environmentally favourable than machining at 150 m/min across all cutting environments. The total carbon emissions (CE_{total}) show an increase of 55.8 %, 41.1 %, 43.4 %, 42 %, 45.5 %, and 43.1 % for C1, C2, C3, C4, C5, and C6 cutting environments, respectively, when comparing the two speeds. Among all the tested cutting environments and speeds, the utilization of the hybrid vegetable oil-based nanofluid-MQL cutting environment proves to be economically viable and environmentally advantageous compared to other cutting environments.

Data availability statement

Data included in article/supp. material/referenced in article.

Code availability

Not applicable.

CRediT authorship contribution statement

Mayur A. Makhesana: Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Harsh Vesuwala:** Writing – original draft, Visualization, Validation, Software, Formal analysis, Conceptualization. **Kaushik M. Patel:** Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Ana Vafadar:** Writing – original draft, Validation, Software, Formal analysis, Conceptualization. **Murat Sarikaya:** Writing – review & editing, Visualization, Conceptualization. **Navneet Khanna:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization, Project Administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Acknowledgement

The authors would like to acknowledge the resources and financial support provided by Nirma University. The sustainability assessment of the experiments was carried out at the Advanced Manufacturing Laboratory at the Institute of Infrastructure Technology Research and Management, India, and the authors are grateful to both the institutes and labs.

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